Construction Contractor Selection: Comparing and Contrasting Data Envelopment Analysis (DEA) and Analytic Hierarchy Process (AHP)

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1.0 Introduction

Due to increases in workplace efficiency and the growth of new businesses, companies have the luxury to select between several different contractors when procuring construction services for all sectors of this industry which hasn't been the case in the past. This makes their decision making process more complex. The complexity of the business world in today's market is opening the door for new technology to assist business owners in their decision making. Several tools have been created to weigh the options according to their value drivers and the business needs of the company[11]. These tools are very useful in the decision making process, yet it is imperative that companies select the appropriate tool that fits the best for their final objective. For instance, Data Envelopment Analysis (DEA) is a common tool used when selecting construction contractors; nevertheless it might not always be the best tool for every single project [5]. There is documentation showing companies having had both successes and failures using DEA as their tool of choice for construction [6].Similarly, we have found studies on the use of Analytic Hierarchy Process (AHP) for company analysis specific to the construction industry. This leads us to believe that there should be an overall analysis done prior to selecting a tool, in order to ensure that it's the appropriate one for that specific project. In this paper, we will use one set of data in two different tools (based on our above mentioned research findings) to figure out which one will have the preferred outcome. Therefore, the two tools we will investigate are Data Envelopment Analysis (DEA) and Analytic Hierarchy Process (AHP) for construction contractor selection.

2.0 Literature Review of DEA and AHP

2.1 Data Envelopment Analysis

Data Envelopment Analysis (DEA), first introduced in 1978 byCharnes et al, uses multiple input variables and creates multiple outputs in order to identify the most efficient peer decision making units (DMUs) [23]. Statistical regressions have been used even prior to Charnes' work, to determine inefficiencies in the performance of DMUs, like the use of OLS (Ordinary Least Squares) regression to evaluate the performance of hospitals in England [22]. DEA has since been utilized and expanded upon by others, including Cooper et al:

> "DEA represents an alternate approach in which frontier values are also used to evaluate performance. It handles multiple inputs and outputs and identifies sources and estimates amounts of inefficiencies in each input or output for every observation and the DMUs associated with these observations" [25].

Some of the core differences, and ultimately a benefit to our work within, is that instead of producing averages like other regression approaches, DEA is deterministic and directed to each (individual) observation [7]. So we understand that DEA is an efficiency assessment tool that has been adopted by many researchers and businesses throughout the world. There is peer-reviewed material available on the subject of DEAas it applies to different sectors such as banking, education and health care [21]. And recently it has been applied specifically to vendor selection

on public procurement [14]. And lastly, DEA has become a useful tool for analysis within the construction industry[15][9][13], wherewe are interested in learning more about recent uses of DEA specific to construction contractor selection. Our utilization of DEAin this regard will follow the ethos of Cooper et al study on RAM (Range Adjusted Measure of Inefficiency) as it pertains to focus only:

> "Our attention focuses on uses in practice by managers, and others, so we apply the following criteria to the measures we discuss: (i) the measures should be readily interpreted for use in a variety of managerial and scientific contexts and (ii) such uses should not require excessively complex mathematical formulations and computations" [24].

Assessment of Criteria for DEA:

In this research paper our DMUs will be construction contractors and the inputs and outputs will align with our sub-criteria chosen for the AHP model. The followingdescriptions explain our methodology for compiling the DEA data that can be seen in the analysis section:

DMUs

Skanska; Andersen; Fortis; P&C; Robinson

Inputs

Start/End Dates: Defined by total working months needed to complete the construction, the lower the number of months, the better. Contractors who did not explicitly address the duration of their proposed work, where given a normalized value of 18-months.Which by our estimation and understanding of commercial construction, would be a leisurely and obtainable duration by all but the least competent contractors (all of these contractors being considered quite competent by the fact that they were personally invited to propose).

Total Project Cost: A common indicator of a contractor's understanding of the project is what they estimate the work to cost for full construction. This cost is discussed frequently in literature and in practice, but with detailed review of these proposals, it wasn't a specific area of discussion. This can be attributed to the fact that the project was in schematic design (SD) during the time of these proposals. We kept things equal for the comparison and scored a value of '1' for each.

Overhead/Profit Costs: Most contractors were silent on this subject with the exception of one who gave general terms for reducing their OH's by approximately 10%. Therefore, we normalized each with a value of '1' and awarded the contractor who documented a reduced OH of '0.9' (again, the lower the better).

Experience Modification Rate (EMR): This is an industry standard rating scale for a construction company's safety performance. In general terms it is the ratio of the company's actual losses to its expected losses (accidents). No company explicitly provided their EMR so we searched company websites (only) to see if they published it. If their website allowed for content search we used both "EMR" and "experience modification rate." If their website didn't have a search function we reviewed content under "safety" (if they had that section), "about us," "experience," "history," and similar. Only one contractor published their EMR that we could find. By definition, an EMR of 1.0 is average, so we normalized everyone to 1.0 but used an actual EMR for the one contractor who published their 0.6 EMR.

Outputs

Number of Milestone: Milestones are another way to judge the contractor understands a new project. We've read about schedule management in the literature and used it in practice. A work breakdown structure (WBS) is very common and helps define with the milestones will be. These milestone then help break up the project into manageable workloads for planning and

execution. We did not have adequate information within the proposals to differentiate the quantity of milestones proposed.

Owner Inclusion in Schedule Process: The normal value for this was ‘1’ and three out of five contractors addressed Owner inclusion. The two that did not address it explicitly were awarded half the value. Our reasoning for providing even this amount is because the contractors expressed their interest in working with the Owner by default, through participation in the proposal effort.

Total Dollar of Value Engineering Ideas: This easily quantifiable value is the sum of all ideas out forth by each contractor in their proposals. These value engineering ideas would reduce the cost of final construction, so the greater the number, the better.

Quantity of Value Engineering Ideas: This is the total count of VE ideas put forth.

Originality of Value Engineering Ideas: We used a 1-3 scale (something allowing differentiation, yet being relatively confined) for scoring the contractors “originality.” Using our construction knowledge of these types of projects we award a greater number for unique and valuable ideas specific to this project.

Owner Risk for Delivery Method: Three out of five contractors shared their preferred delivery method (CM/GC, construction management / general contractor) for how they would execute the work. Some went into detail on subcontracting delivery methods, based on scope.Overall, project risk is important to mitigate and the contractors who didn’t address this at all were awarded ‘0’ in our first analysis. But without weight restriction in our model, we chose to run the analysis again with a non-zero value of ‘0.1’ so that shortcoming wouldn’t be concealed. Both results are discussed in the analysis.

Involvement of the Local Community: This criterion is important in most construction projects. For the project we are using, it’s very important because the size of the community is smaller and the local population has a great interest in their new public school. Again, some

contractors did not address this subject at all, and others did in varying degrees. We retained the confined scoring range of 0-3 (using ‘0’ and next ‘0.1’ as above), the greater the better.

Relevance of Delivery: Our scoring of this criterion ended up mirroring the above Owner Risk so in a sense it becomes a redundant category. The basis for defining the relevance of delivery is to align the proposed delivery method of the contractor to their typical delivery method used on other projects. As an example, if a contractor proposed CM/GC delivery but we know in industry they exclusively build in the hard bid environment (design-bid-build), then it’s not a proper alignment of their skills to the Owner’s needs. We didn’t find any misalignments in this category.

2.2 Analytical Hierarchy Process

The complexity of the business world in today’s market is opening the door for new technology to assist business owners in their decision making. Several tools have been created to weigh the options according to their importance and the specific needs of the company[11]. These tools are very useful in the decision making process, yet it is imperative that companies select the appropriate tool that fits the best for their final objective. Data Envelopment Analysis (DEA) is the common tool used when selecting construction contractors; nevertheless it might not always be the best tool for every single project. A lot of companies have had a lot of successes and failures using DEA as their tool of choice which leads us to believe that there should be an analysis done prior to selecting a tool to ensure that it’s the appropriate one for that specific project.

Today’s business world gives organizations the opportunity to choose from a wide variety of options which require an in-depth analysis of all the alternatives. The decision making process has tangible and intangible criteria that one needs to take into consideration and analyze alongside one another in accordance to their importance to the specific goal. According to Thomas L. Saaty, the founder of AHP, “The Analytical Hierarchy Process (AHP) is a theory of measurement through pairwise

comparisons and relies on the judgments of expert to derive through priority scales" [18]. AHP is a tool used by organizations to help them analyze complex decisions so that they can make an informed decision according to their needs [1]. AHP doesn't necessarily give the "right" answer to a problem, instead it aides decision makers by creating a framework that allows them to analyze multiple alternatives through a set of criteria and sub-criteria so that they can choose the one that fits their particular needs [16]. The AHP tool is frequently used in various environments such as healthcare, education and business to name a few. Once a company decides the goal that they would like to achieve for particular project, they then create a hierarchical model to analyze all the important aspects that can affect their project whether they are of the upmost importance or not [8]. The AHP model process can be broken down into these steps.

Analytic Hierarchy Process	
Step 1	State the goal you would like to achieve
Step 2	Build the model with the components (criteria, sub criteria and alternatives)
Step 3	Do a pairwise comparison of components in respect to the goal
Step 4	Calculate the maximum eigenvalue of the pairwise comparison
Step 5	Calculate weighing and consistency index in a matrix
Step 6	Calculate the consistency ratio (CR must be less than .1 or if not reassessment of AHP is needed)
Step 7	Assess the alternatives in reference to weighting

Table 1: The Steps of the Analytic Hierarchy Process [20]

Below is the table that Saaty created and is used by companies to do pairwise comparison when they are ranking the components of the hierarchical model according to their importance. The rating scale range is from 1/9 to 9, one being of equal importance, nine being absolutely more important and one over nine being absolutely less important. When comparing two criteria such as X and Y, if X is absolutely more important it then would be given a 9 and Y would be given a 1. Any organization that chooses to use the AHP model for their decision making process would use this rating system to for all the criteria that they list [19].

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two factors contribute equally to the objective
3	Somewhat more important	Experience and judgment slightly favor one over the other
5	Much more important	Experience and judgment strongly favor one over the other
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is the highest possible validity.
2, 4, 6, 8	Intermediate values	When compromise is needed

Table 2: The Saaty Rating Scale [19]

AHP Pairwise Matrix (PWM)

The pairwise matrix is a positive reciprocal matrix and is shown in Figure 4. To calculate the pairwise matrix, each criterion is scored against each other by using the Saaty 9-value scale method[20]. AHP depend on pairwise comparisons to obtain numerous priority weights between design alternatives and value attributes which lead to the overall ranking of design alternatives. The weighting process is so sensitive that any minor differences in the weighting can change the final outcome [12].

Let A=pairwise matrix

A $=\{a_{ij}\}$, where $a_{ij}=\frac{W_i}{W_j}$ and W_i the weight of the i^{th} criterion

	Z_1	Z_2	…	Z_n
Z_1	$\frac{W_1}{W_1}\frac{W_1}{W_2}$	…		$\frac{W_1}{W_n}$
Z_2	$\frac{W_2}{W_1}\frac{W_2}{W_2}$	…		$\frac{W_2}{W_n}$
…	…	…	…	…
Z_n	$\frac{W_n}{W_1}\frac{W_n}{W_2}$	…		$\frac{W_n}{W_n}$

Figure 1. Pairwise weighting matrix (PWM) of AHP

To reduce human bias and the margin of error due to the limitation of the Saaty 9-value method, consistency index is needed and calculated as follows:

$CI = \frac{\lambda max - n}{n-1}$ Where n is the number of criteria and λ the max eigenvalue [10]

The consistency ratio is then found by dividing the consistency index with average random consistency and the acceptable CR is less than 0.1and is only applicable with the original scale[10] [17].

$CR = \frac{CI}{RI}$

Case Study Comparing Simple Weighting to AHP:

In a similar study done in Taiwan, AHP was compared to the Simple Weighting (SW) in two construction contractor projects using the Best Value (BV) approach. The BV has been implemented in contractor selection process in many countries around the world and is also known as the optimal outcome of a business process. The BV method is comprised of several tasks which include identifying criteria and sub-criteria, scoring the bidders using the criteria and finally selecting a winner. In this study, two public construction projects were selected for this investigation. The same data was used in both the SW and AHP to weigh the decision criteria in a pairwise comparison. Through this study they were able to see that the weighting of a criterion differed greatly depending on the method used. Each level of the hierarchical model for both SW and AHP had a large difference in the weighting. For instance, the differences in the weighing vary from 58-80%. Each tool gives the highest importance to different criteria. According to the study, the weighing process for SW method is done within a group which allows for dominate personalities to impose their views, thus making the results less accurate and bias. On the other hand, the AHP tool allows members of a committee to weigh the criteria separately therefore reflecting an honest opinion [20].

The study shows some pros and cons from both tools. The SW process is a lot faster than AHP and took only an hour to complete, but can be bias and inaccurate, whereas AHP took several days due to reassessment caused by the consistency ratio being above the required 0.1. Additionally, experts tend to under rate criteria in which they have expertise and over rate those where they don't. To minimize this inconsistency, the author recommendsincorporating a variety of experts from all backgrounds and educating them prior to weighing process. Moreover, it is best to use the least amount of levels of decision criteria to reduce the AHP processing time. Table 3 reflects the time that was required to run SW and AHP from start to finish. AHP was done manually, whereas AHP-1 and AHP-2 were computerized [20].

	SW	AHP	AHP-1	AHP-2
No. of PWMs in a circle		7	7	7
Processing time of a PMW		2.5 hours	15 Min	15 Min
Processing time of 1 circle		7 days	105Min (15*7)	105Min (15*7)
Processing time of 4 circles		7 + 18 days	420 Min(=105*4)	210 Min(=105*2)
Total duration	1 hour	25 days	7 hours	3.5 hours

Table 3. Time required to weight criteria using SW and AHP [20]

Assessment of Criteria for AHP:

The assessment was completed by sending out the pairwise comparison survey to all the experts through several methods of communication including email, the postal service and hand delivery to make sure the received it within adequate time to complete. Next, each expert was contacted via telephone or personally to explain in detail how the scoring process works. After everyone completed their survey independently, they were evaluated and 49 of the 98 had a consistency ratio of less than 0.1, so the other 49 experts had to reassess their score. Throughout the second assessment, 33 of the 49 were satisfactory which require a third assessment for the remaining 16 experts. During the third assessment, 13 more were approved. Finally, the last three were accepted in the fourth assessment. It took four assessments to finally have each completed with a CR of less than 0.1 which shows how time consuming the AHP

process can be if not done properly. Table 4 below shows the average CR and the amount of accepted surveys during each assessment cycle[20].

Table 4: Assessment Cycle of AHP [20]

Attributes	First	Second	Third	Fourth
No. of PWMs performed	98	49	16	3
No. and % of unacceptable PWMs	49 (50%)	16 (32.7%)	3(18.75%)	0(0%)
Average CR	0.142	0.101	0.085	0.063

3.0 Methodology

For our effort of finding a preferred construction contractor selection methodology, we began with a relevant literature review. This included the above mentioned findings on DEA and AHP both in general terms and as they have been previously utilized in the construction world. We found articles on combined approaches, where multiple authors integrated DEA and AHP into a decision making model (Bowen 1990; Shang and Sueyoshi 1995; Yang et al 2002; Korpela et al 2007; Wang et al 2007). We don't go into detail on each of these past contributions but instead provide reference for further study, and move forward to expand our subject with other applicable data. Because of these findings and our desire to add original contribution to academia, we decided to enhance our methodology by inserting a real world construction contractor selection exercise. The following data and analysis section introduces our project and presents an opportunity for us to test the theory of using both a DEA, and an AHP method. And since the project we present has since been proposed on, a construction contractor selected, and the project physically completed, we will also be able to test our findings against what the project

stakeholder team executed.

The authors decided to use actual contractor proposals from a publicly funded construction project in our region. General contractors submitted proposals to one of the authors as the acting Owner's Representative of a local School District, and therefore these proposals can be re-evaluated in accordance with the methodology of this paper. The authors will analysis this data first through the lens of AHP and then utilize DEA to compare and contrast the results. All findings can be reviewed against the actual contractor award made by the School District for further perspective and learning.

Project:

- Vernonia School District K-12 replacement school

General Contractors Proposing (not exhaustive):

- Skanska
- Andersen
- Fortis
- P&C
- Robinson

Initial Criteria/ sub-criteria for assessment:

1. Schedule/Phasing
    - Start/end dates
    - Quantity of proposed milestones
    - Inclusion of owner in schedule process

2. Overall Budget
    - Total project cost estimated
    - $-amount for OH, profit, soft costs, etc.

3. Value Engineering Ideas
    - Total $ of ideas proposed
    - Quantity of ideas proposed
    - Originality of VE ideas (subjective sliding scale)

4. Delivery and execution approach
    - ESH (safety) via EMR
    - Risk level to owner for proposed delivery method
    - Involvement level of local community (subjective sliding scale)
    - Relevance of proposed method to company typical method used

4.0 DataAnalysis

AHP Method:

The AHP model is generally used as a decision making tool to help organizations decide on the most suitable solution for a particular objective. Contrary to standard decision-making tools, AHP uses pairwise comparison which allows members to express their opinions verbally on criteria while making the results more accurate. What makes AHP unique is that it can measure tangible and intangible elements which help check the consistency of the results therefore giving more credibility to the final

decision. When an organization is embarking on a complex project, they first need to solidify a goal and then divide it into criteria, sub-criteria and alternatives as seen in Figure 1 [3].

Figure 2: AHP Model

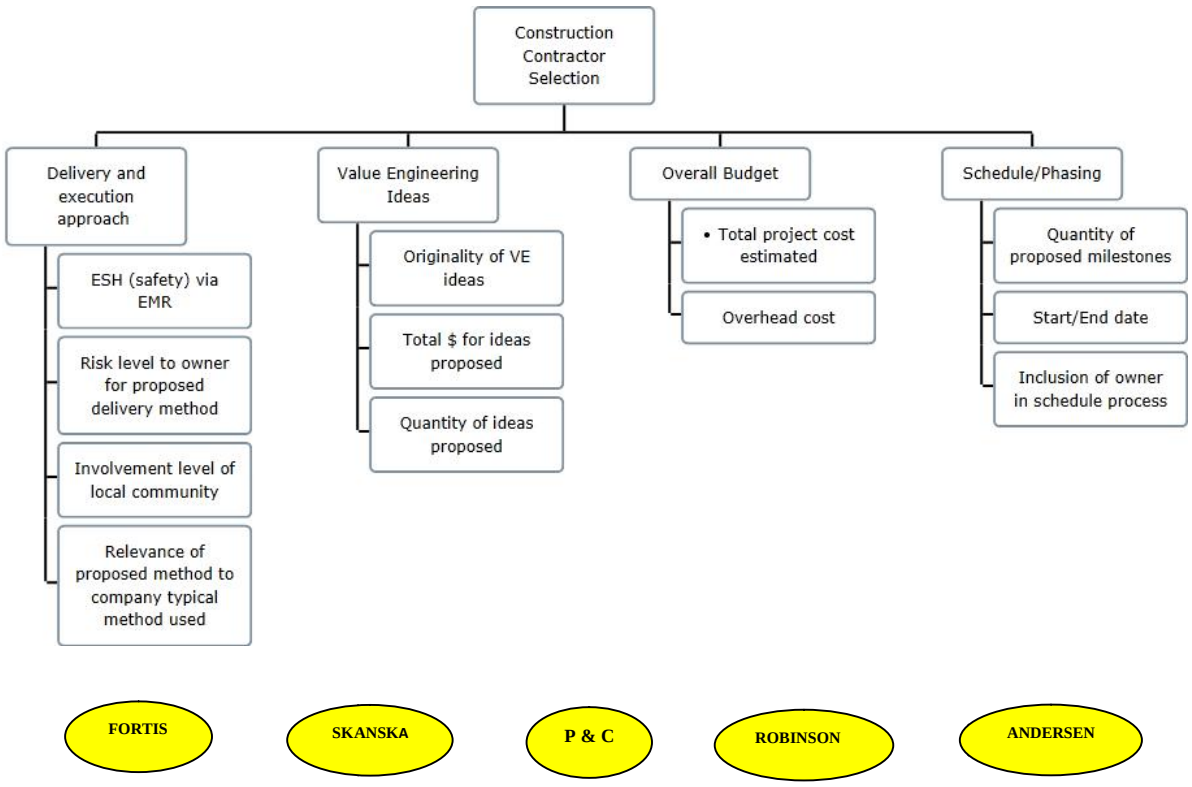


Table 5: Criteria Definition

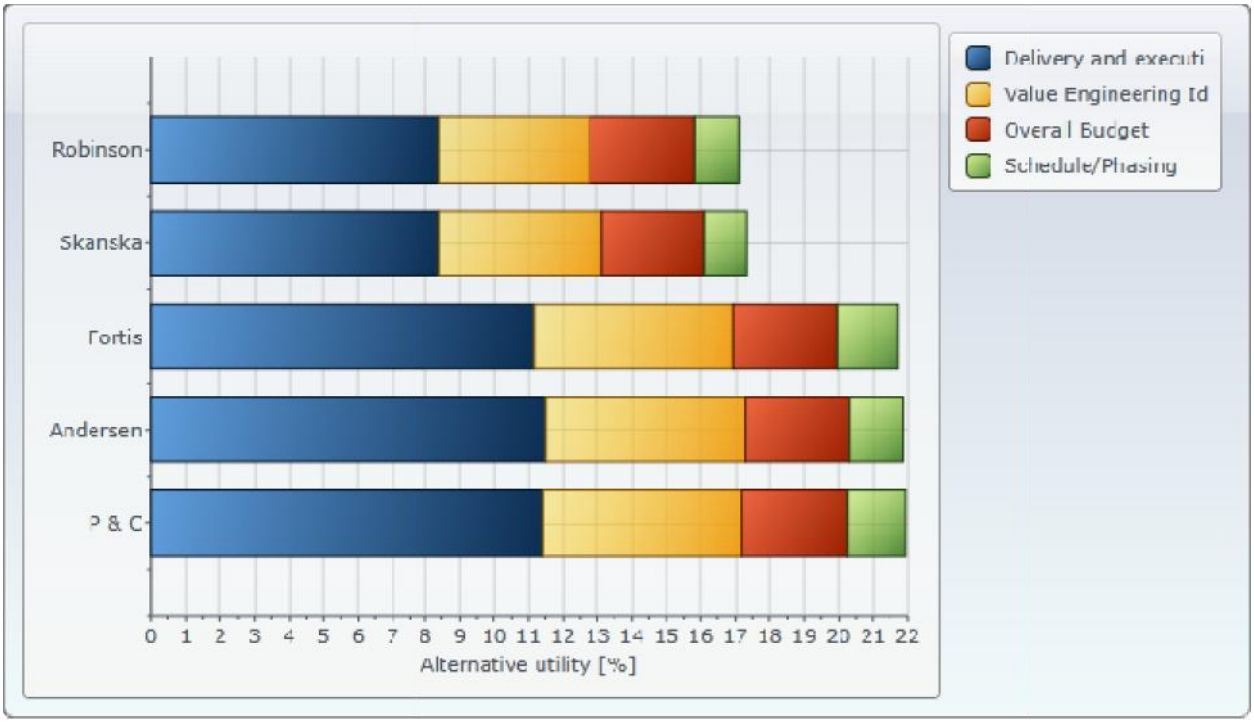
Company (DMU)	Criteria	Sub-criteria	Description of Sub-Criteria
Skanska	Schedule/ Phasing	Start/end dates	Is the Contractor proposing an early start date (are they prepared to begin) and do they have an aggressive construction schedule to finish as early as possible (EF, early finish).
Robinson		Quantity of proposed milestones	The further they have defined the work scope breakdown, the better.
Andersen		Inclusion of owner in schedule process	Does the Contractor discuss an Owner feedback loop within schedule creation and

			ongoing administration?
P & C	Overall Budget	Total project cost estimated	Has the Contractor defined the overall project budget, and if so, what is the cost? (lower is better)
Fortis		$-amount for OH, profit, soft costs, etc	Has the Contractor defined their mark-ups? Are they an expensive machine of a company to manage this or do they run an efficient construction management team while being cost-sensitive for the Owner's benefit?
	Value Engineering	Total $ of ideas proposed	What is the total value of the VE ideas put forth by the Contractor? (more is better)
		Quantity of ideas proposed	How many ideas has the Contractor put forth? 1-2 ideas means they didn't study the project much, several ideas means they can be critical about VE and therefore benefit the Owner.
		Originality of VE ideas	Are their VE ideas basic, non-value added ideas that already exist within industry? Or are they truly original and project-specific VE ideas?
	Delivery and Execution Approach	ESH (safety) via EMR	ESH (safety) via EMR What is their EMR (Experience Modification Rate)? 1.25 or higher is "high hazard" company, under 1.0 is expected, the lower the better.
		Risk level to owner for proposed delivery method	Is the Contractor proposing a delivery method (hard bid their subcontractors, typical CM/GC, IPD, etc.) that is in line with the Owner's best interest and therefore mitigates the chances of surprises?
		Involvement level of local community	Is the Contractor proposing to include the community in the execution of their work? (better if they do include the community)
		Relevance of proposed method to company typical method used	Is the Contractor proposing a delivery method that is typical of how they perform other projects? Or are they proposing something that is new to them where they don't have a proven track record?

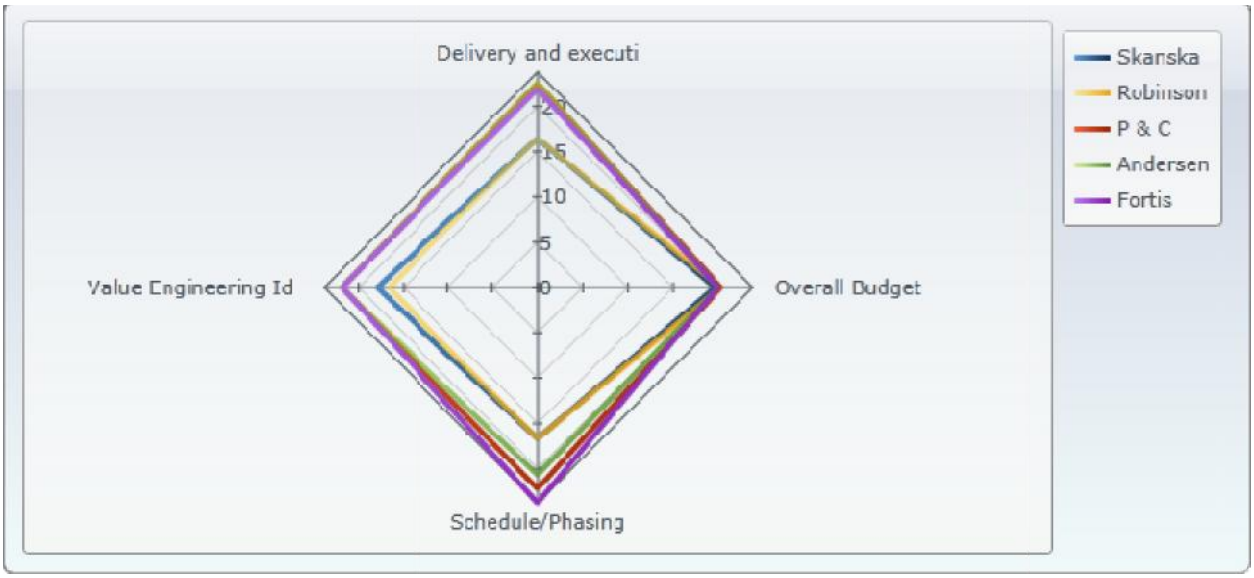
AHP Results

Expert I

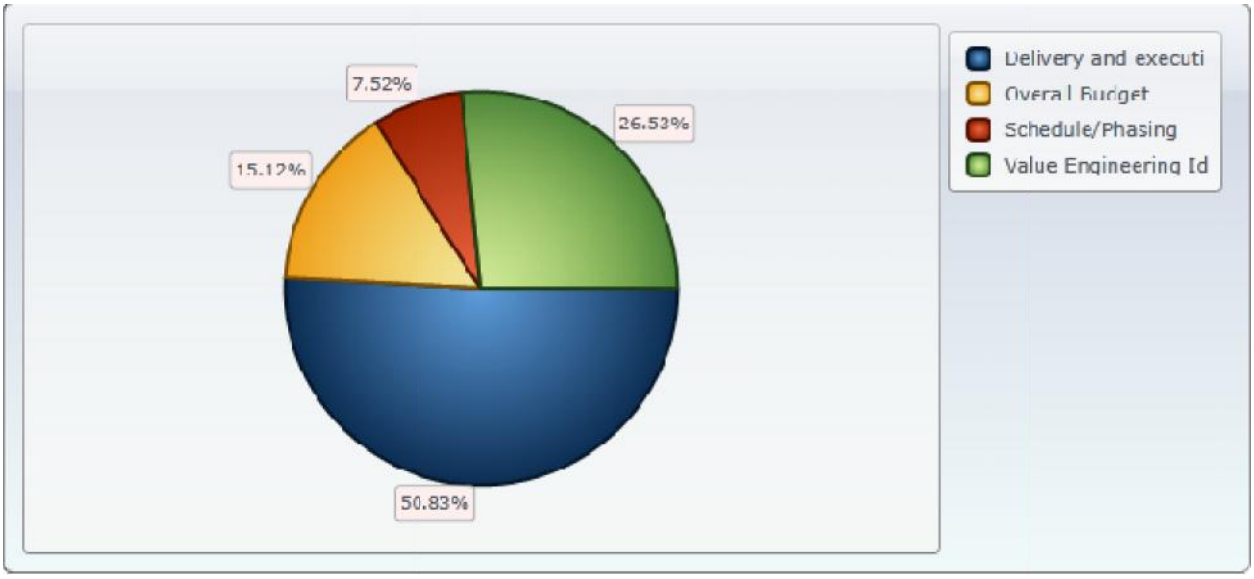
Alternatives Ranking



Alternatives Comparison

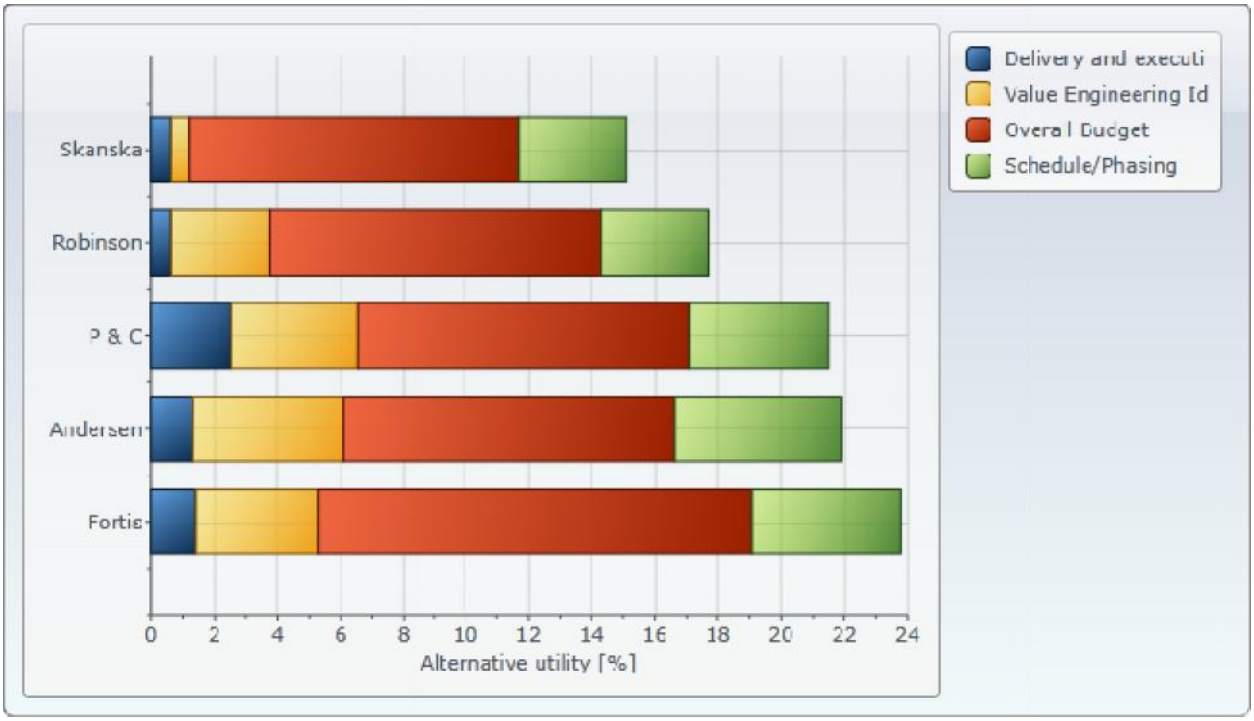


Sub-Criteria Weights

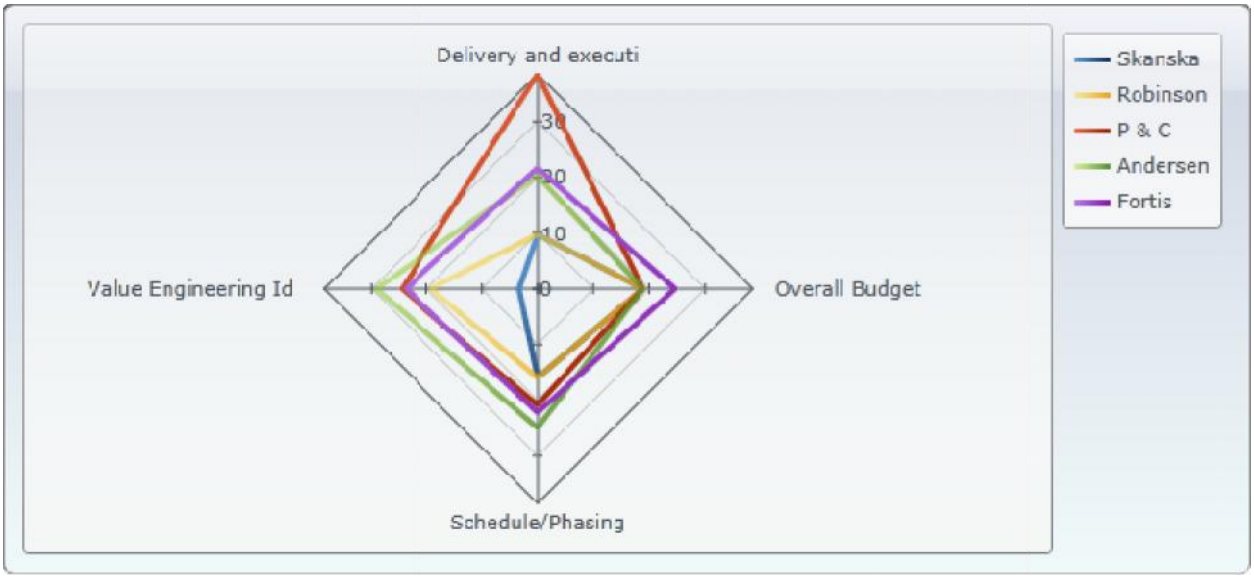


Expert II

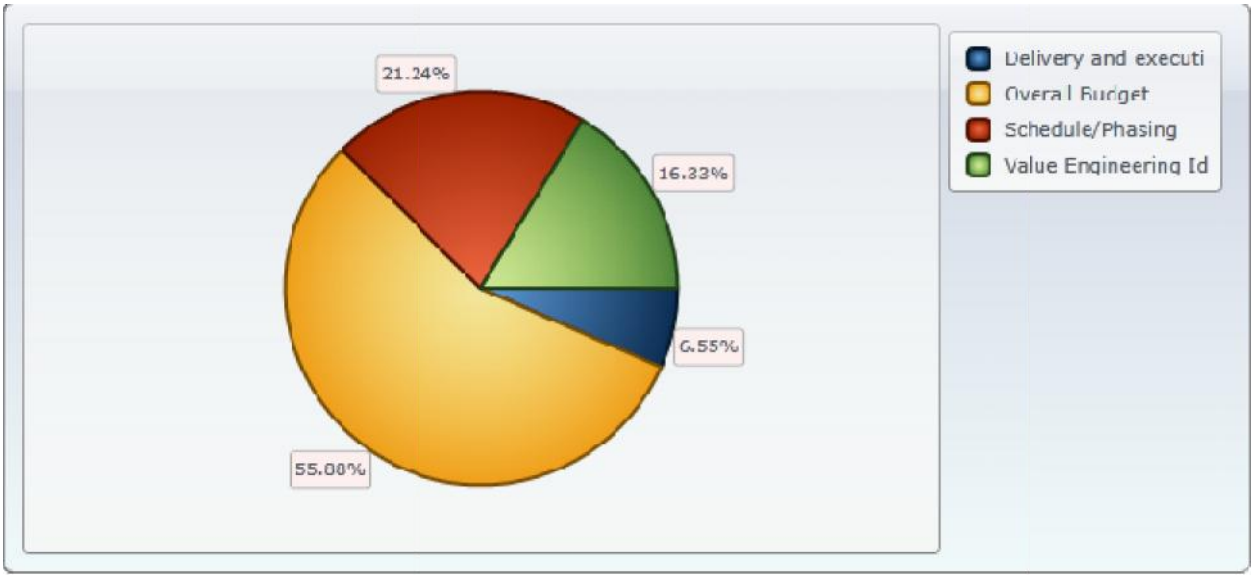
Alternatives Ranking



Alternatives Comparison

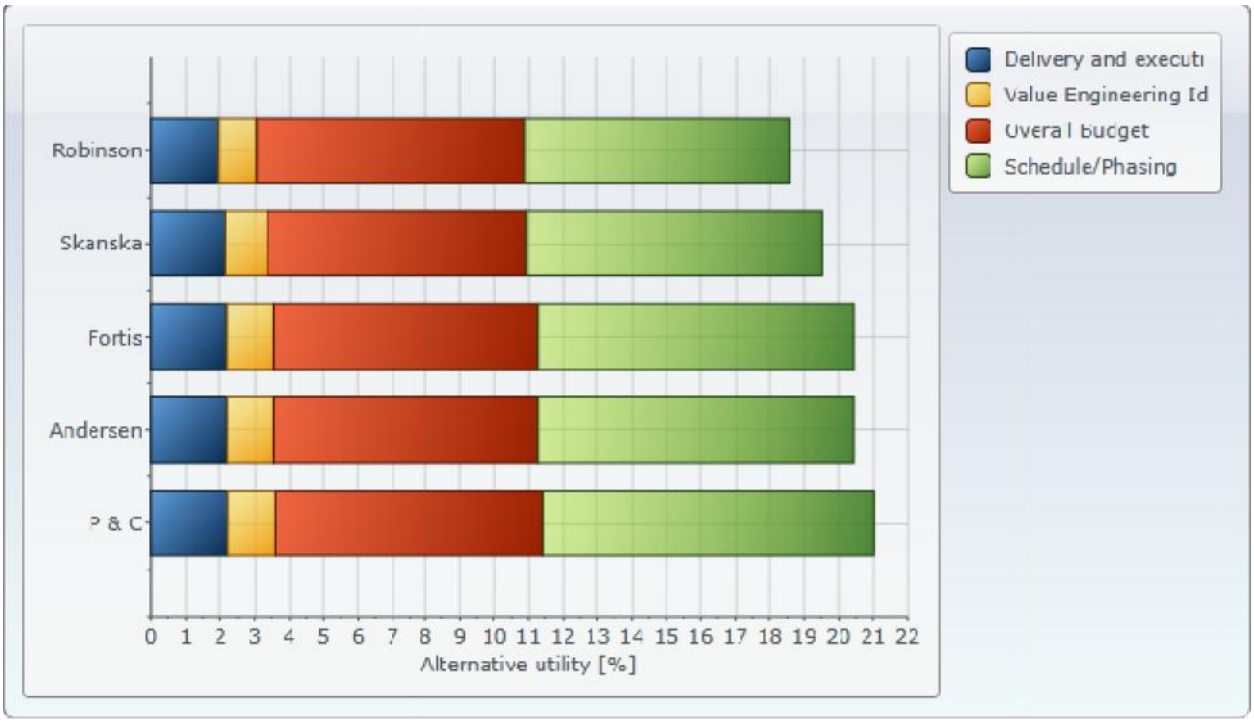


Sub-criteria Weights

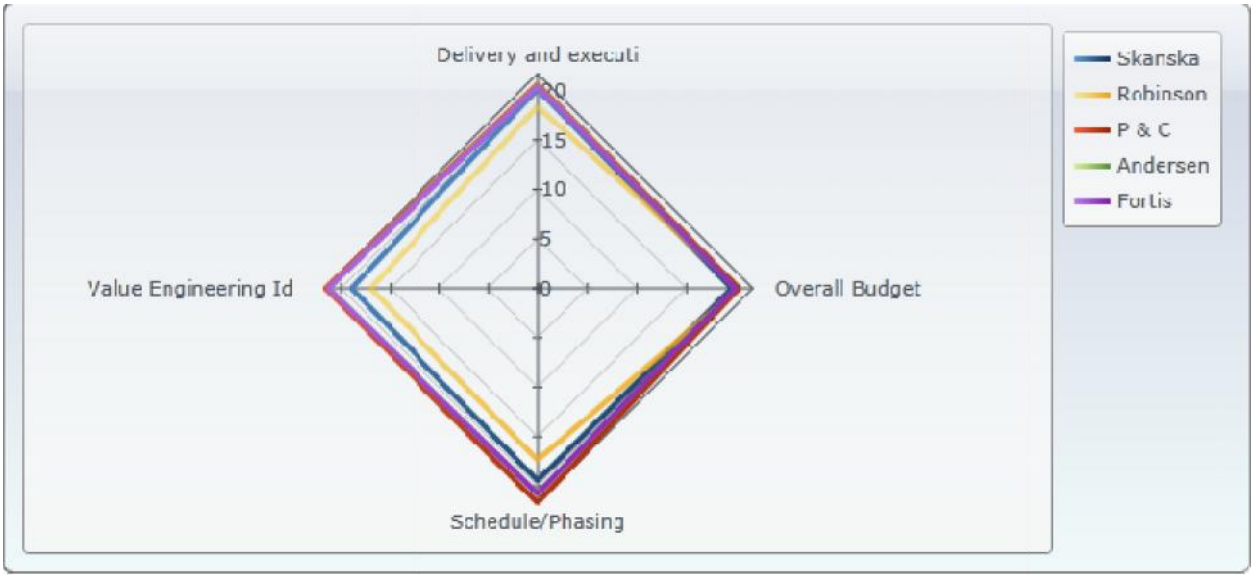


Expert III

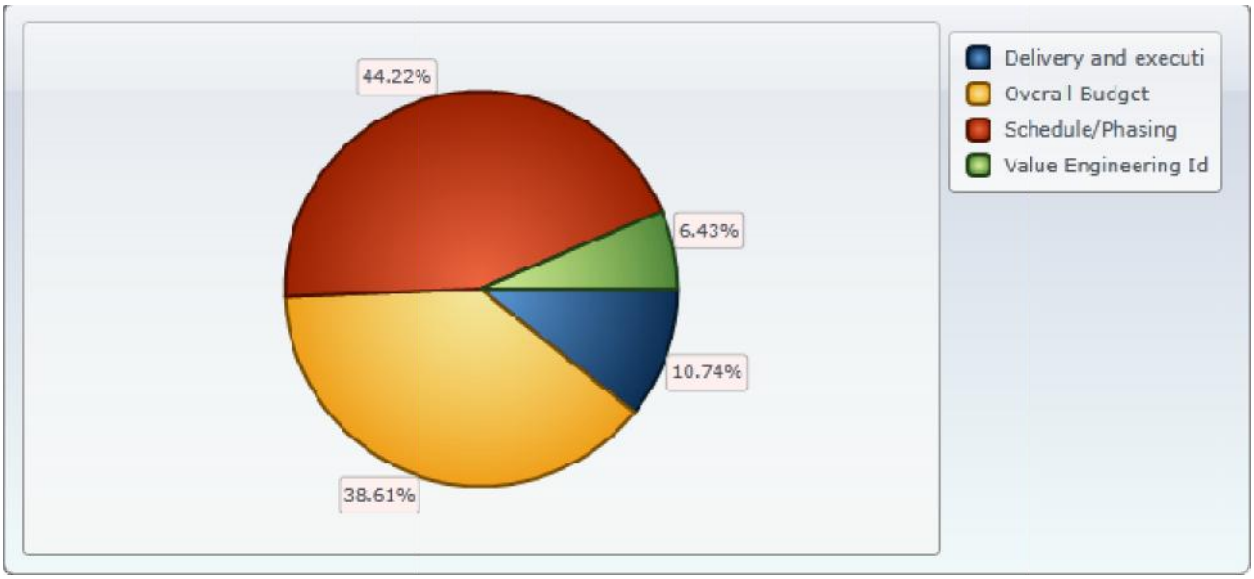
Alternatives Ranking



Alternatives Comparison



Sub-criteria Weights



DEA Model

We utilized the DEAFrontierfree version (Dr. Joe Zhu's research), which is excel based with a solver add-in. For our model we allowed the use of the ‘0’ value where contractors did not explicitly provide information relevant to a given criterion.And without utilizing weight restriction in this free version, we may have allowed some contractors to benefit from not addressing each and every subject. This provides

for the ability to conceal negative information to some extend but we believe the model provided efficiency ratings accurately enough to reflect our inputs and outputs.

DMU | Inputs

Company	Start/end dates	Total project cost	Overhead/Profit costs	EMR (safety)
Skanska	18	1	0.9	1
Andersen	16	1	1	0.6
Fortis	16	1	1	1
P&C	12	1	1	1
Robinson	18	1	1	1

DMU |Outputs (1 of 2)

Company	# of milestones	Iclude Owner schedule	Total $ of VE	# of VE ideas
Skanska	1	0.5	1910000	17
Andersen	1	1	2170671	10
Fortis	1	1	2315800	19
P&C	1	1	2550000	13
Robinson	1	0.5	593753	13

DMU |Outputs (2 of 2)

Company	Originality of VE	Owner risk for delivery	Involve local community	Relevance of delievery
Skanska	2	0	0	0
Andersen	2	3	3	3
Fortis	3	3	1	3
P&C	3	3	3	3
Robinson	1	0	0	0

Results of DEA Model:

Results	**Score**	**Rank**
Skanska	111.11%	4
Andersen	166.67%	2
Fortis	135.29%	3
P&C	171.43%	**1**
Robinson	100.00%	5

5.0 Conclusion

Our DEA model selected P&C as the most efficient selection for the case of the VernoniaSchool District project, followed by Andersen, Fortis, Skanska and lastly Robinson. Our AHP model showed relative similarities between some of the contractors, selecting two groups: A tie for last (Skanska and Robinson) and the balance tied for first (Andersen, Fortis, P&C). The difference between the two models is substantial and interesting to learn in this setting of utilizing a real past project to aid our understanding. We hoped to ultimately make a recommendation on which model better fits the construction contractor selection process. We believe we can make a recommendation, but only by quantifying how we got to a decision.

The DEA model provided us a neat and precisely calculated efficiency rating for which contractor to select, and we appreciate the decisiveness of the model. But when we look back on the process to get those efficiencies it doesn't seem as justifiable (strong) as it could be. We believe that having one person, even being a "construction expert" in the field make the data entry, it leaves the door open for subjectivity and perhaps misunderstanding. In our above DEA model description we justify each of the criteria and normalize the values or calculate values as much as possible. But it still seems less defendable for a dynamic construction related selection process such as we had.

We found our application of AHP to have positive and negative attributes as well. Our top positive attributes include the multiple stakeholder scoring ability and the weighted value that we captured through comparison of criteria against each other. The biggest negative attribute is the ability to have a tie in the scoring, thus providing a less-than-deterministic final model recommendation. We learned that all (4-total) of ourconstruction experts spent at least an hour studying and completing the AHP scoring model. Some took several tries with daily correspondence with us on how the (makeitrational) online survey functioned. Some initially scored on a scale of 1 to 10 when we asked for 1 to 100. Others completed part of the model but

omitted other parts. It was cumbersome to manage and we're thankful to have had only a limited number of participants. We believe that the difficulties they experienced can be summarized with two concerns: 1. Incomplete contractor proposals left them confused on how to score criterion that were not explicitly addressed. 2. The AHP model and web based scoring system was completely foreign to most of them (1-expert has a Ph.D and has used AHP extensively so he only experienced item #1 above).

Based on these findings, we recommend and quantify that AHP is a better application for the construction contractor selection process than DEA for a number of reasons:

- DEA produces too detailed of an efficiency rating based on less than perfectly quantified data that we often find in construction contractor proposals
- DEA is directly managed by a single team member, and while peers might provide input or clarification along the way, it is not structured for multiple, independent scoring
- AHP has the ability to scale with the project and accept inputs (scoring) by multiple people in a private and secure manner, thus lessening the impact of peer bias and group think
- If a project team is proactive to establish the AHP model in advance of seeking proposals, they can require explicit and directly relevant data from each of the contractors, thus reducing subjectivity
- Lastly, and specific to construction contractor selection, AHP allows for varied weights of criteria by each and every team member, more easily than DEA (at least our DEAFrontier free version) so when stakeholders from different projects address a new model they can immediately influence what criteria matter most

6.0 Recommendation for Further Study

Based on the above, the authors recommend AHP over DEA for the specific use of construction contractor selection. We make this recommendation based on a real world construction project, and having run the same data separately through each model. Our first recommendation for future studies would be to create the model in advance of requesting contractor proposals, not to fit a model to a past project theoretically, based on industry norms and literature review.

Within the DEA we could get more detail into the model that could help us refine our analysis, such as inclusion of weight restrictions as mentioned above. Also within DEA, the utilization of our real world project example gave us something applicable to study, but by no means where the contractor's proposals complete. This affected our study by reducing the number of elements that we could compare between companies. In fact, this even caught some of our construction experts so off guard that they were asked to score candidates in sections that didn't have explicit values noted in the proposals. An example of this is the safety criterion, EMR. The authors mentioned in the DEA introduction that EMR had to be normalized to a value of '1' and then we had to perform research on each company in hopes of learning what their exact EMR is. We came up mostly empty handed on this one particular criterion. So in future studies it might be wise to not have categories for comparable criteria even if it's standard content in industry and/or literature. A gate or filter process at the front end would be helpful to reduce or eliminate such anoccurrence.

7.0 Bibliography

[1] F. D. Felice and A. Petrillo, “A multiple choice decision analysis: an integrated QFD – AHP model for the assessment of customer needs,” *International Journal of Engineering, Science and Technology*, vol. 2, no. 9, pp. 25–38, 2010.

[2] G. A. Forgionne, R. Kohli, and D. Jennings, “An AHP analysis ofquality in AI and DSS journals,” *Omega, the International journal of Management Science*, vol. 30, pp. 171–183, 2002.

[3] D. Dalalah, F. AL-Oqla, and M. Hayajneh, “Application of the Analytic Hierarchy Process (AHP) in Multi- Criteria Analysis of the Selection of Cranes,” *Jordan Journal of Mechanical and Industrial Engineering*, vol. 4, no. 5, pp. 567–578, Nov. 2010.

[4] D.-Y. Chang, “Applications of the extent analysis method on fuzzy AHP,” *European Journal of Operational Research*, vol. 95, pp. 649–655, 1996.

[5] B. McCabe, V. Tran, and J. Ramani, “Construction prequalification using data envelopment analysis,” *Canadian Journal of Civil Engineering*, vol. 32, no. 1, pp. 183–193, Feb. 2005.

[6] R. Bendaña, A. del Caño, and M. Pilar de la Cruz, “Contractor selection: fuzzy-control approach,” *Canadian Journal of Civil Engineering*, vol. 35, no. 5, pp. 473–486, May 2008.

[7] M. S. El-Mashaleh, “Decision to bid or not to bid: a data envelopment analysis approach,” *Canadian Journal of Civil Engineering*, vol. 37, no. 1, pp. 37–44, Jan. 2010.

[8] H.-P. Fu, Y.-C. Ho, R. C. Y. Chen, T.-H. Chang, and P.-H. Chien, “Factors affecting the adoption of electronic marketplaces: A fuzzy AHP analysis,” *International Journal of Operations & Production Management*, vol. 26, no. 12, pp. 1301–1324, 2006.

[9] I. E. Tsolas, “Modelling profitability and effectiveness of Greek-listed construction firms: an integrated DEA and ratio analysis,” *Construction Management and Economics*, vol. 29, no. 8, pp. 795–807, Aug. 2011.

[10] C. Kahraman, N. Ç. Demirel, and T. Demirel, “Prioritization of e-Government strategies using a SWOT-AHP analysis: the case of Turkey,” *European Journal of Information Systems*, vol. 16, no. 3, pp. 284–298, Jul. 2007.

[11] L. Rabelo and et al., “Supporting Simulation-Based Decision Making with the Use of AHP Analysis,” in *Winter Simulation Conference*, 2005.

[12] L. ZHU, A. K. AURUM, I. GORTON, and R. JEFFERY, “Tradeoff and Sensitivity Analysis in Software Architecture Evaluation Using Analytic Hierarchy Process,” *Software Quality Journal*, vol. 13, pp. 357–375, 2005.

[13] G. H. J. Williams and T. R. Anderson, “Use of DEA to Evaluate Non-linear and Imprecise Information in Construction Contractor Performance,” in *Technology Management for Reshaping the World*, Portland, OR, 2003.

[14] M. Falagario, F. Sciancalepore, N. Costantino, and R. Pietroforte, “Using a DEA-cross efficiency approach in public procurement tenders,” *European Journal of Operational Research*, vol. 218, no. 2, pp. 523–529, Apr. 2012.

[15] M. S. El-Mashaleh, S. M. Rababeh, and K. H. Hyari, “Utilizing data envelopment analysis to benchmark safety performance of construction contractors,” *International Journal of Project Management*, vol. 28, no. 1, pp. 61–67, Jan. 2010.

[16] J. Korpela, A. Lehmusvaara, and J. Nisonen, “Warehouse operator selection by combining AHP and DEA methodologies,” *International Journal of Production Economics*, vol. 108, no. 1–2, pp. 135–142, Jul. 2007.

[17] J.Mustajoki and R.P. Hanmalainen, “Web-Hipre: Global Decision Support by Value Tree and AHP Analysis,” *INFOR: Information Systems and Operational Research*, vol. 38, no. 3, pp. 208-220, Aug. 2000.

[18] T. Saaty, “Decision making with the analytic hierarchy process,” *Int. J. Services Sciences*, Vol. 1, No. 1, pp. 83-97, 2008.

[19] G. Coyle, “The Analytic Hierarchy Process (AHP),”Pearson Education, pp. 1-11, 2004.

[20] W. Wang, W. Yu, I. Yang, C. Lin, M. Lee, Y. Cheng, “Applying the AHP to Support the Best-Value Contractor Selection- Lessons Learned from Two Case Studies in Taiwan,” *Journal of Civil Engineering and Management,* vol. 19 (1), pp. 24-36, 2013

[21] Emrouznejad, A., Parker, B. R., & Tavares, G. “Evaluation of research in efficiency and productivity: A survey and analysis of the first 30 years of scholarly literature in DEA,” *Socio-economic Planning Sciences, 42,* 3, 151-157, January 2008.

[22] Feldstein, M. S. “Multicollinearity and the Mean Square Error of Alternative Estimators,” *Econometrica, 41,* 2, 337-346, March 01, 1973.

[23] Liang, L., Cook, W. D., & Zhu, J. “DEA models for two-stage processes: Game approach and efficiency decomposition,” *Naval Research Logistics, 55,*7, 643-653, October 01, 2008.

[24] Cooper, W. W., Park, K. S., & Pastor, J. T. “RAM: A Range Adjusted Measure of Inefficiency for Use with Additive Models, and Relations to Other Models and Measures in DEA,” *Journal of Productivity Analysis, 11,* 1, 5, February 01, 1999.

[25] Bardhan, I. R., Cooper, W. W., &Kumbhakar, S. C. “A Simulation Study of Joint Uses of Data Envelopment Analysis and Statistical Regressions for Production Function Estimation and Efficiency Evaluation,” *Journal of Productivity Analysis, 9,* 3, 249, March 01, 1998.